Discovery of Photospheric Calcium Line Strength Variations in the DAZd White Dwarf G29-38

Ted von Hippel[1,2] and Susan E. Thompson[3]

ABSTRACT

Metals in the photospheres of white dwarfs with T_{eff} between 12,000 and 25,000 K should gravitationally settle out of these atmospheres in 1–2 weeks. Temporal variations in the line strengths of these metals could provide a direct measurement of episodic metal accretion. Using archival VLT and Keck spectroscopy, we find evidence that the DAZd white dwarf G29-38 shows significant changes in its Ca II K line strength. At the two best-observed epochs, we find that the Ca line equivalent width (EW) = 165 ± 4 mÅ (in 1996.885) and 280 ± 8 mÅ (in 1999.653), which is an increase of 70%. We consider the effect that pulsation has on the Ca EWs for this known variable star, and find that it adds an error of < 1 mÅ to these measurements. Calcium line strengths at other observational epochs support variations with timescales as short as two weeks. These Ca EW variations indicate that the metal accretion process in G29-38, presumably from its debris disk, is episodic on timescales of a few weeks or less, and thus the accretion is not dominated by Poynting-Robertson drag from an optically thin, continuous disk, which has a timescale of ∼ 1 year.

Subject headings: accretion, accretion disks — stars: individual (G29-39) — white dwarfs

1. Introduction

The presence of Ca, Mg, Fe, or other heavy elements in the photospheres of hydrogen-dominated (DA) white dwarfs (WDs) poses a long-standing problem. The high surface gravities of WDs cause their atmospheres to become highly stratified and theory predicts

[1]Department of Astronomy, University of Texas at Austin, 1 University Station C1400, Austin, TX 78712-0259, USA; ted@astro.as.utexas.edu

[2]Visiting Scientist, Southwest Research Institute, 1050 Walnut St., Suite 400 Boulder, CO 80302

[3]The Colorado College, 14 E. Cache La Poudre, Colorado Springs, CO 80903

that these heavy elements will settle on timescales of 10^{-2} to 10^6 years (Dupuis et al. 1992; Koester & Wilken 2006), depending on the mass and surface temperature of the white dwarf. Yet most WDs are old, and almost every known DAZ, as these stars are now called (Sion et al. 1983), has been cooling as a WD for at least 10^8 years, and usually 10^9 years or more. The timescale problem is less extreme for metals in the rarer helium-dominated (DB) white dwarfs, since the depletion of metals due to diffusion at the bottom of the He-convection zone is slower than at the bottom of the H-convection zone and since the higher transparency of helium atmospheres makes lower metal abundances more visible.

Heavy elements have been known in WD atmospheres for almost 50 years (in the DB vMa 2; Weidemann 1958), though the first convincing demonstration of metals in a DA was not until Lacombe et al. (1983). It took another 14 years to find the second and third DAZs (Koester et al. 1997; Holberg et al. 1997). The DAZ sample then began to grow with the breakthrough survey of Zuckerman & Reid (1998), which yielded seven to nine new DAZs. Subsequent modern surveys (e.g., Zuckerman et al. 2003) have shown that $\sim$25% of all single DAs possess metals in their photospheres. On the theoretical side, early work focused on understanding how WDs might accrete sufficient material from the interstellar medium (ISM) to maintain metals in their atmospheres. Some researchers (Dupuis et al. 1993; Koester & Wilken 2006) concluded that ISM accretion is the source of the photospheric metals, while other researchers (Aannestad et al. 1993; Zuckerman & Reid 1998; Zuckerman et al. 2003; Kilic & Redfield 2007) concluded that ISM accretion is insufficient. An alternative hypothesis, that DAZs accrete their metals from circumstellar material, has gone from an intriguing possibility based on just one DAZ with a debris disk (G29-38, Zuckerman & Becklin 1987), to a compelling scenario, especially now that five debris disk white dwarfs are known, all of which happen to be DAZs (Becklin et al. 2005; Kilic et al. 2005, 2006; von Hippel et al. 2007; Kilic & Redfield 2007). These DAZs with debris disks are now known as DAZd white dwarfs (von Hippel et al. 2007). The newly discovered debris disk WDs, the high relative frequency of DAZs and their plausible connection to circumstellar debris (e.g., Jura 2003), as well as new catalogs of DAZs (Zuckerman et al. 2003; Koester et al. 2005), have created new opportunities to understand the origin of DAZs and their accretion processes.

In this paper we study archival time-series spectroscopy from multiple epochs of the luminosity variable DAZ white dwarf G29-38 (=WD2326+049). The case for Ca line strength variations in G29-38 is complicated since this star is a pulsating WD. The parameters for G29-38 are $T_{\rm eff}$ = 12100, log(g) = 7.9, log(Ca/H) = -6.8 (Koester et al. 2005), distance = 19 pc (Harrington & Dahn 1980), or log(g) = 8.14 (Bergeron et al. 1995). The timescale for gravitational settling in this star is 7 days according to Koester & Wilken (2006), shorter for the higher log(g) of Bergeron et al. (1995), and therefore Ca line strength variations are plausible. After accounting for the effects of pulsation, we find clear evidence that the Ca II K line strength varies in this star. Metal line strength variability is a new tool for the study of accretion onto WDs and it may eventually help us unravel the source(s) of metals found in DAZ atmospheres.

2. Observations

Both van Kerkwijk et al. (2000) and Thompson et al. (2007) published time-series spectroscopy of G29-38 in order to measure the spherical degree of pulsation modes via line shape variations of the Balmer series. We use these spectra to measure the Ca II K line strength present in this star. On November 19, 1996, van Kerkwijk et al. (2000) obtained 4.72 hours of continuous (no readout gaps) 12s exposures of G29-38 with the Low Resolution Imaging Spectrometer on the Keck II Telescope. The resolution was set by the seeing to be ~ 7 Å, and the average spectrum has a signal-to-noise of 1000 measured at the continuum near 5000 Å. For the same purposes, on August 27, 1999, Thompson et al. (2007) obtained 6.14 hours of continuous spectroscopy with the FORS1 spectrograph on the VLT (see also Thompson 2006). Each of the 604 spectra has an exposure time of 16 s and a resolution of ~ 8 Å. The average spectrum has a signal-to-noise of 500 measured at the continuum near 5000 Å. Thompson (2006) and Thompson et al. (2007) performed standard reductions on both sets of data, except that flat fields and traditional flux calibrations were not possible for either dataset. In both cases the average spectra are visibly smooth near 4000 Å, and we have determined that the lack of flat-fields has a negligible effect on our EW measurements. In both datasets, the Ca II 3933 Å line is clearly visible, a fact that we utilize to demonstrate EW variations between these two observations.

3. Calcium Equivalent Width Measurements

In Figure 1 we present the average Ca II K line region of G29-38 at two epochs, 1996.885 and 1999.653. The average spectrum taken with the Keck telescope in 1996 shows an obvious Ca II K line with EW = 165 ± 4 mÅ. The average spectrum taken with the VLT in 1999 shows a deeper Ca line with EW = 280 ± 8 mÅ, an increase of 70%. Formally, these two observations differ by 12.9 σ. Each are measured by fitting a Gaussian to the spectral line and the errors are those associated with that fit.

We need to ensure that the pulsations of G29-38, which produce brightness variations as high as 3% for a single pulsation, are not responsible for the changes in Ca line strength.

The pulsating modes cause changes in surface temperature and radial velocity fields, both of which can alter the measured absorption lines. Since the 1996 and 1999 data sets are time series of spectra, we measure how the EW changes over the pulsation cycle and how this change is reduced by integrating over the extended periods of the Keck and VLT observations. Using these measurements, we demonstrate (see below) that the pulsations have a negligible effect compared to the observed 70% change in EW of the average spectra.

We measured the equivalent width for each spectrum of both the Keck and VLT data sets by fitting a Gaussian to the calcium line after normalizing the spectra. We fit an 8th-order polynomial across 20 Å on each side of the Ca II K line of the average spectrum. We removed the curvature induced by the broad hydrogen lines on either side of the Ca line by dividing each spectrum by this fit to the average. These flattened spectra were normalized as we fit the Gaussian function by allowing the overall flux of the spectrum to vary during the fit. During the fit, the area and FWHM of the Gaussian were allowed to vary.

We performed a Fourier Transform (FT) on the time-series Ca EW measurements (Figure 2). These FTs provide a clear indication of how much the line strength can change during a single observing run due to pulsation effects. The EW FTs clearly show that the pulsations are stronger during the Keck epoch. The flux amplitude of the largest observed pulsation (measured at 615s) in the VLT data is 2.7% (Thompson et al. 2007) while the largest mode (measured at 614s) in the Keck data is 3.17% (van Kerkwijk et al. 2000). Therefore, one would expect the Keck observations to exhibit larger variations in Ca equivalent width. The equivalent width amplitude of these largest flux modes are 7.1% and 13.8%, with the Keck amplitude being 1.9 times larger than the VLT amplitude. See Table 1 for the amplitude of the EW variations measured at the dominant modes in each data set. Finally, we calculate the average value of the measured equivalent widths, weighted by the errors established from fitting the Gaussian. The values 167 ± 1.7 mÅ for the Keck epoch and 272 ± 1.9 mÅ for the VLT epoch (an increase in 63%) are in close agreement with the equivalent width of the unweighted average spectrum.

The pulsations cause deviations from the average equivalent width. Observing an incomplete cycle of a dominant pulsation can result in an abnormally high or low measurement of the average EW. To determine how large this effect could be, we calculated a worst case for this star. This worst case provides an outer bounds for our data set (useful for our error analyses, below) and should help future observers who wish to repeat this experiment with G29-38, possibly with long exposures that do not resolve the pulsation modes. We combined six modes with semi-amplitude (mean to maximum) EW variations of 8, 12, and 15% (2 each) and we chose periods from 1150 to 600 seconds based on previous observations (see Figure 3 for the specific modes). Since the modes of G29-38 vary in strength with time, this allows for maximal pulsations (which are larger amplitude modes than we actually observed in the Keck and VLT data). This approach also encompasses the possibility of observing a few large amplitude modes along with a few moderate amplitude modes. Figure 3 shows the possible range of EW values in percentage terms ((max EW - min EW) / mean EW) due to only partial averaging over pulsation modes, as a function of cumulative exposure times. For an extremely short exposure time, we could observe an EW difference as large as $\sim$100% given the semi-amplitudes of the modes introduced in this example. After one hour of cumulative exposure, the maximum expected EW difference due to the pulsation modes of this star drop to 5%. After 3.5 hours this effect is $< 1.5\%$.

Since the VLT and Keck spectra are time series, we know the size of the Ca EW variations and can better estimate the error associated with partial averaging. Including only the three largest pulsations of the Keck data and averaging over a total of 4.7 hours spaced in 24s intervals (identical to the Keck observations), we find a deviation of less than 0.3% in the EW. This translates to at most an additional error of 0.5 mÅ and 0.8 mÅ for the Keck and VLT measurements, respectively. This is equivalent to one third of the error in the weighted average and one tenth of the error from fitting the average spectrum. We conclude that partial averaging over the pulsations cannot account for the observed 70% variation between the measured Ca EW in 1996 at Keck and 1999 at the VLT.

In summary, we find that the EW of Ca increased by 63-70% between 1996.885 and 1999.653. The difference between these two estimates is likely dominated by subtle differences in how we measure EWs, and this range is a useful estimate of the accuracy in the measured change in Ca EWs. Only a negligible amount of this 63-70% change is due to residual, unaccounted-for pulsation effects.

Besides these two epochs with time-series spectroscopy, we were able to derive Ca EWs for nine additional spectra of G29-38, kindly provided to us by D. Koester. Two spectra of 30 minute duration each were observed with the Calar Alto 2.2m Cassegrain spectrograph on September 18 and 20, 1995. These spectra were the source of the discovery by Koester et al. (1997) that G29-38 is a DAZ. Due to the temporal proximity of the Calar Alto observations, we averaged together the spectra before measuring the Ca EW. This averaging also decreased the spectral noise and reduced the pulsation error. Five spectra of 30 minute duration each were observed with Keck, one on the night of July 7, 1997, one on the night of December 10, 1998, and three on the night of August 12, 1999. To increase the signal-to-noise for August 12, 1999, we averaged together the spectra from this night before measuring the Ca EW. Two additional spectra of 5 minute duration were obtained at VLT/UVES on the nights of August 6, 2000 and September 17, 2000. Further details on the observations and data quality for these spectra can be found in Koester et al. (2001), Koester et al. (2005), and Zuckerman et al. (2003). From these nine additional spectra we derive Ca EWs at six additional epochs. All of these measured Ca EWs, as well as the two derived from the time-series spectroscopy discussed above, are presented in Figure 4. The error bars represent the 1 σ quadrature combination of the Ca EW measurement uncertainty and the expected EW variation caused by sampling over partial luminosity periods. Figure 3 represents the maximum observed error from partial averaging and thus we use these values as a 3σ estimate for this error for all epochs except the two discussed above, where we directly measure the amplitude of the pulsation modes.

4. The Source of Calcium Line Strength Variations

Since G29-38 has a debris disk known to be rich in refractory elements (Reach et al. 2005), it is natural to assume that the Ca variations we see are due to time-variable accretion from the disk. There is, however, another possibility worth considering—that this object has a large star spot that covers more or less of the observed face of G29-38 at the different observational epochs. Such star spots models have been proposed before to explain variations in He line strength in three WDs with mixed H/He atmospheres, G104-27 (Kidder et al. 1992), PG1210+533 (Bergeron et al. 1994), and HS0209+0832 (Heber et al. 1997). For a model of G29-38 with steady-state accretion and a magnetically constrained star spot, the spot could either be enriched in Ca with respect to the rest of the star if accretion occurs within the spot, or it could be depleted in Ca if accretion occurs elsewhere. Since the variation in Ca EW is nearly a factor of two (Fig. 4), even in a model with dramatically different Ca abundances within and outside the spot, the spot would have to cover nearly half of a WD hemisphere. It seems unlikely that such a spot could persist for years, particularly for this pulsating WD with pulsations sloshing across the surface every few minutes. A prediction of the star spot model is that the Ca EW should be modulated on the timescale of the rotation period. This effect would be particularly apparent with observations covering two or more rotation periods. G29-38 appears to be rotating with v sin(i) = 11–28 km s^{-1} (Berger et al. 2005), or a period of $\leq$ 900–2400 s or 2000–5000 s, assuming a radius consistent with log(g) = 8.14 or 7.9, respectively. Our VLT and Keck time-series observations cover 4.72 and 6.14 hours, so if the star spot model were correct, the rotation period would have to be meaningfully longer than 6 hours, which is inconsistent with the measured rotation velocity. In summary, we consider the star spot scenario highly unlikely, yet future observations with better temporal sampling will be needed to convincingly rule it out.

The history of Ca EWs in G29-38 presented in Figure 4 shows that the Ca line strength varies by at least a factor of two, that significant variations occur on timescales as short as 15 days (August 12, 1999 to August 27, 1999), and possibly that there is a typical Ca EW $\approx$ 230 mÅ with periods of both higher and lower Ca line strength. Assuming that the Ca EW variations are caused by time-variable accretion from G29-38's debris disk, the low Ca EW in late 1996 indicates that accretion decreased dramatically for at least one settling time (expected to be $\sim$ 7 days; Koester & Wilken 2006). The variations in August 1999 similarly indicate an increased accretion rate with a timescale of $\sim$ 2 settling times. Further observations and analysis are required for this star in order to determine the minimum timescale and range for accretion events, as well as to observationally test the theoretical gravitational settling time.

We note also that D. Koester kindly searched through multiple spectra of 24 DAZs from the SPY survey (Napiwotzki et al. 2001; Koester et al. 2005) for us in order to search for other WDs with varying Ca EWs. He found no other convincing cases. Perhaps a larger sample of stars or more spectra per star are needed. In any case, further examples besides G29-38 would help clarify whether episodic accretion is a function of other system parameters and would help test the theoretically determined residence timescale for metals in DAZ atmospheres.

5. Conclusions

We find that the Ca II K line in G29-38 varies from EW = 165 $\pm$ 4 mÅ in 1996.885 to EW = 280 $\pm$ 8 mÅ in 1999.653, or a factor of $\sim 1.7\times$ between these two epochs. Fully taking into account variations in G29-38's EW due to sampling effects over its multi-period pulsations, we find that the EW variations are essentially unaffected over these 4.72 hour and 6.14 hour time-series observations. We also measure Ca EWs in this star for a further six epochs and find convincing evidence that the Ca line changes on timescales as short as 15 days. These Ca line-strength variations indicate that the source of the variations, presumably metal accretion from the debris disk, is not a steady-state process and varies on timescales of a few weeks. Observations with greater temporal sampling are required to determine the timescale range of G29-38's episodic accretion.

Our Ca EW measurements may already provide insight into the physics governing accretion onto this star. For instance, if accretion is dominated by Poynting-Robertson (P-R) drag from the known debris disk, then the dust accretion timescale is $4r^2a$ years (Reach et al. 2005), where r is the particle distance in solar radii and a is the particle radius in microns. Spitzer mid-IR spectroscopy (Reach et al. 2005) indicates sub-micron silicate particles. With an inner debris disk edge at $\leq 0.15\ R_\odot$ (von Hippel et al. 2007), the P-R timescale at the inner disk edge is $\leq$ 33 days, consistent with the Ca EW variations, especially if whatever process feeds dust to the inner disk edge is discontinuous. This scenario argues against an optically thin (in the radial direction) debris disk extending continuously to 1 $R_\odot$ or beyond. Comparing these timescales indicates that G29-38's debris disk is likely to be optically thick with collisional processes or dust delivery radially through an optically thick disk setting the accretion timescale.

Due to the short settling times of metals in their atmospheres, warm ($T_{\rm eff}$ = 12,000–25,000 K) DAZs are an excellent place to look for Ca (or other metal) line strength variations. Will other DAZs that harbor debris disks show Ca line strength variations? And if so, will the timescale or range of these variations be correlated with any of the debris disk properties? Will DAZs without detectable debris disks show Ca line strength variations? Answers to these questions will help us understand the accretion process operating in these systems and possibly give us clues to the origins of white dwarf surface metals. Additionally, the timescale of metal line strength variations as a function of stellar effective temperature would provide the first observational test of the theoretically determined residence timescale for metals in DAZ atmospheres.

We thank Detlev Koester for his many excellent spectra of G29-38, and for considerable consultation on WD models and this paper. We thank Marten van Kerkwijk for his reductions of the Keck data and Mike Montgomery for helpful discussions. We thank our referee, Ralf Napiwotzki, for his insights and for comments that improved the presentation. TvH gratefully acknowledges support as a visiting scientist from the Southwest Research Institute. This material is based upon work supported by the National Aeronautics and Space Administration under Grant No. NAG5-13070 issued through the Office of Space Science.

REFERENCES

Aannestad, P. A., Kenyon, S. J., Hammond, G. L., & Sion, E. M. 1993, AJ, 105, 1033

Becklin, E. E., Farihi, J., Jura, M., Song, I., Weinberger, A. J., & Zuckerman, B. 2005, ApJ, 632, L119

Berger, L., Koester, D., Napiwotzki, R., Reid, I. N., & Zuckerman, B. 2005, A&A, 444, 565

Bergeron, P., Wesemael, F., Beauchamp, A., Wood, M. A., Lamontagne, R., Fontaine, G., & Liebert, J. 1994, ApJ, 432, 305

Bergeron, P., Wesemael, F., Lamontagne, R., Fontaine, G., Saffer, R. A., & Allard, N. F. 1995, ApJ, 449, 258

Dupuis, J., Fontaine, G., Pelletier, C., & Wesemael, F. 1992, ApJS, 82, 505

Dupuis, J., Fontaine, G., & Wesemael, F. 1993, ApJS, 87, 345

Harrington, R. S., & Dahn, C. C. 1980, AJ, 85, 454

Heber, U., Napiwotzki, R., Lemke, M., & Edelmann, H. 1997, A&A, 324, L53

Holberg, J. B., Barstow, M. A., & Green, E. M. 1997, ApJ, 474, L127

Jura, M. 2003, ApJ, 584, L91

Kidder, K. M., Holberg, J. B., Barstow, M. A., Tweedy, R. W., & Wesemael, F. 1992, ApJ, 394, 288

Kilic, M., & Redfield, S. 2007, ApJ

Kilic, M., von Hippel, T., Leggett, S. K., & Winget, D. E. 2005, ApJ, 632, L115

Kilic, M., von Hippel, T., Leggett, S. K., & Winget, D. E. 2006, ApJ, 646, 474

Koester, D., et al. 2001, A&A, 378, 556

Koester, D., Provencal, J., & Shipman, H. L. 1997, A&A, 320, L57

Koester, D., Rollenhagen, K., Napiwotzki, R., Voss, B., Christlieb, N., Homeier, D., & Reimers, D. 2005, A&A, 432, 1025

Koester, D., & Wilken, D. 2006, A&A, 453, 1051

Lacombe, P., Wesemael, F., Fontaine, G., & Liebert, J. 1983, ApJ, 272, 660

Napiwotzki, R., et al. 2001, Astronomische Nachrichten, 322, 411

Reach, W. T., Kuchner, M. J., von Hippel, T., Burrows, A., Mullally, F., Kilic, M., & Winget, D. E. 2005, ApJ, 635, L161

Sion, E. M., Greenstein, J. L., Landstreet, J. D., Liebert, J., Shipman, H. L., & Wegner, G. A. 1983, ApJ, 269, 253

Thompson, S. E. 2006, in ASP Conf. Ser. 352: New Horizons in Astronomy: Frank N. Bash Symposium, ed. S. J. Kannappan, S. Redfield, J. E. Kessler-Silacci, M. Landriau, & N. Drory, 289

Thompson, S. E., van Kerkwijk, M. H., & Clemens, J. C. 2007, in prep van Kerkwijk, M. H., Clemens, J. C., & Wu, Y. 2000, MNRAS, 314, 209

von Hippel, T., Kuchner, M. J., Kilic, M., Mullally, F., & Reach, W. T. 2007, ApJ

Weidemann, V. 1958, PASP, 70, 466

Zuckerman, B., & Becklin, E. E. 1987, Nature, 330, 138

Zuckerman, B., Koester, D., Reid, I. N., & Hünsch, M. 2003, ApJ, 596, 477

Zuckerman, B., & Reid, I. N. 1998, ApJ, 505, L143

Table 1. EW Variations for Different Periods in the Keck and VLT Data.

period (1)	Amp (mÅ) (2)	Amp (%) (3)
Keck (1996.885)		
614.25	23 ± 3	13.81 ± 1.8
817.66	18 ± 3	10.03 ± 1.8
653.08	5 ± 3	2.95 ± 1.8
775.97	10 ± 3	5.24 ± 1.8
VLT (1999.653)		
615.371	20 ± 4	7.1 ± 1.4
810.759	20 ± 4	7.4 ± 1.4
835.283	17 ± 4	6.2 ± 1.4
353.469	1 ± 4	0.4 ± 1.4

References. — We fit the series of EW measurements with periods found by van Kerkwijk et al. (2000) and by Thompson et al. (2007) for the Keck and VLT observations, respectively. We present the amplitude of the changing EWs in milli-Ångstroms and in percentages. The errors represent the formal errors from the fits.

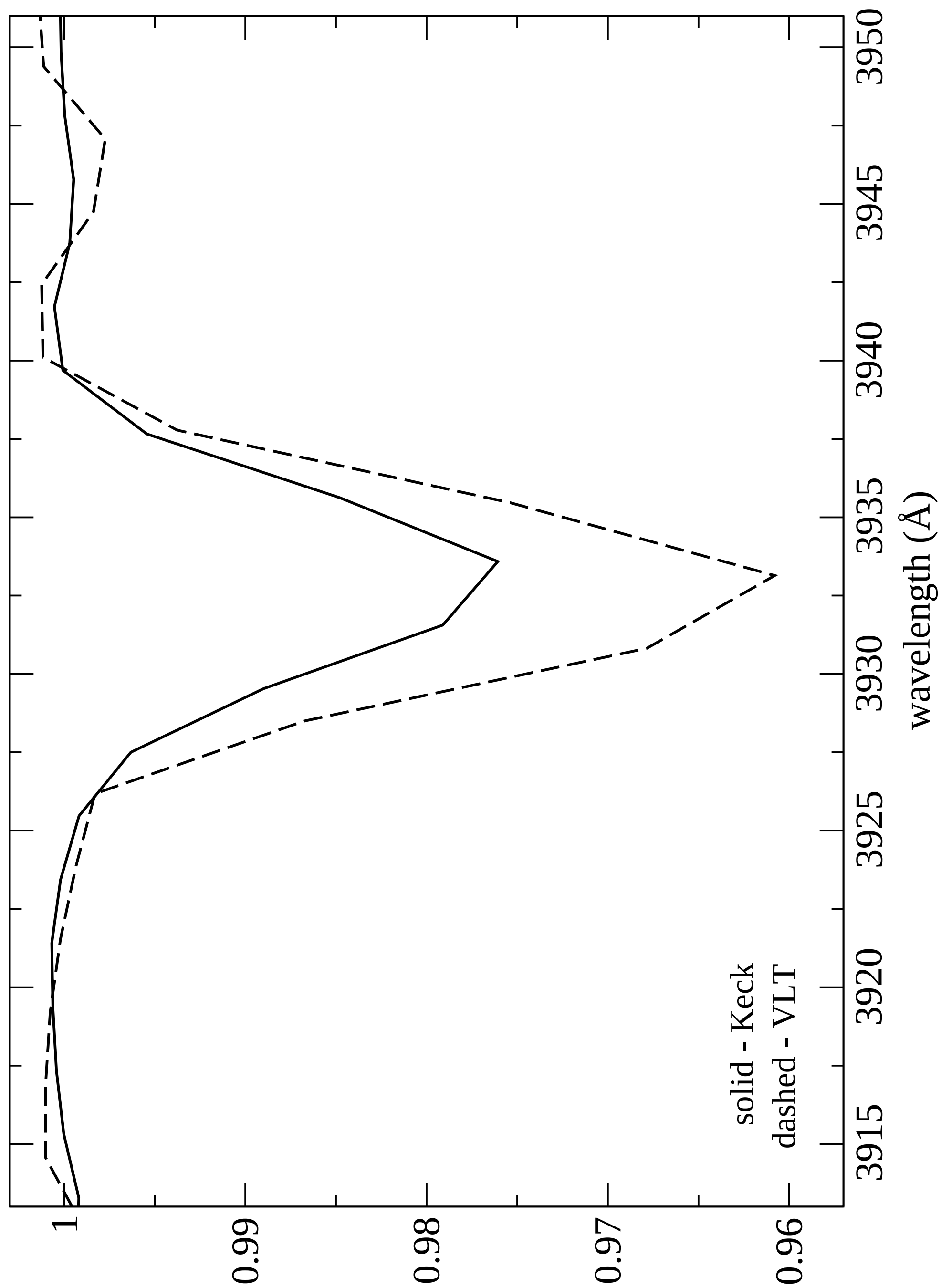

Fig. 1.— The Ca line region in G29-38 at two different epochs, 1996.885 and 1999.653. The data are the averaged, normalized spectra.

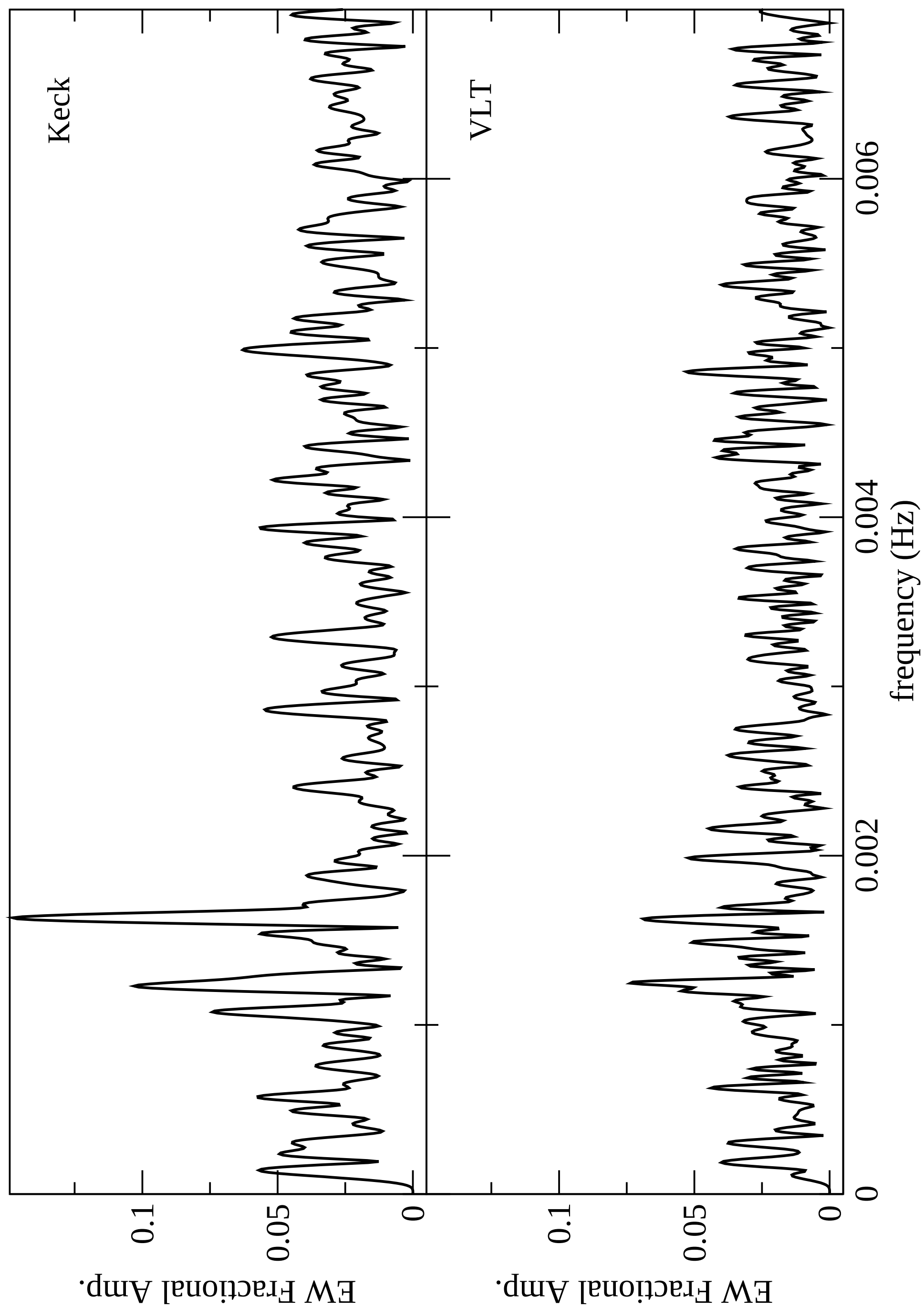

Fig. 2.— Fourier Transforms of the Ca EWs from the 1996.885 Keck spectroscopy and the 1999.653 VLT spectroscopy.

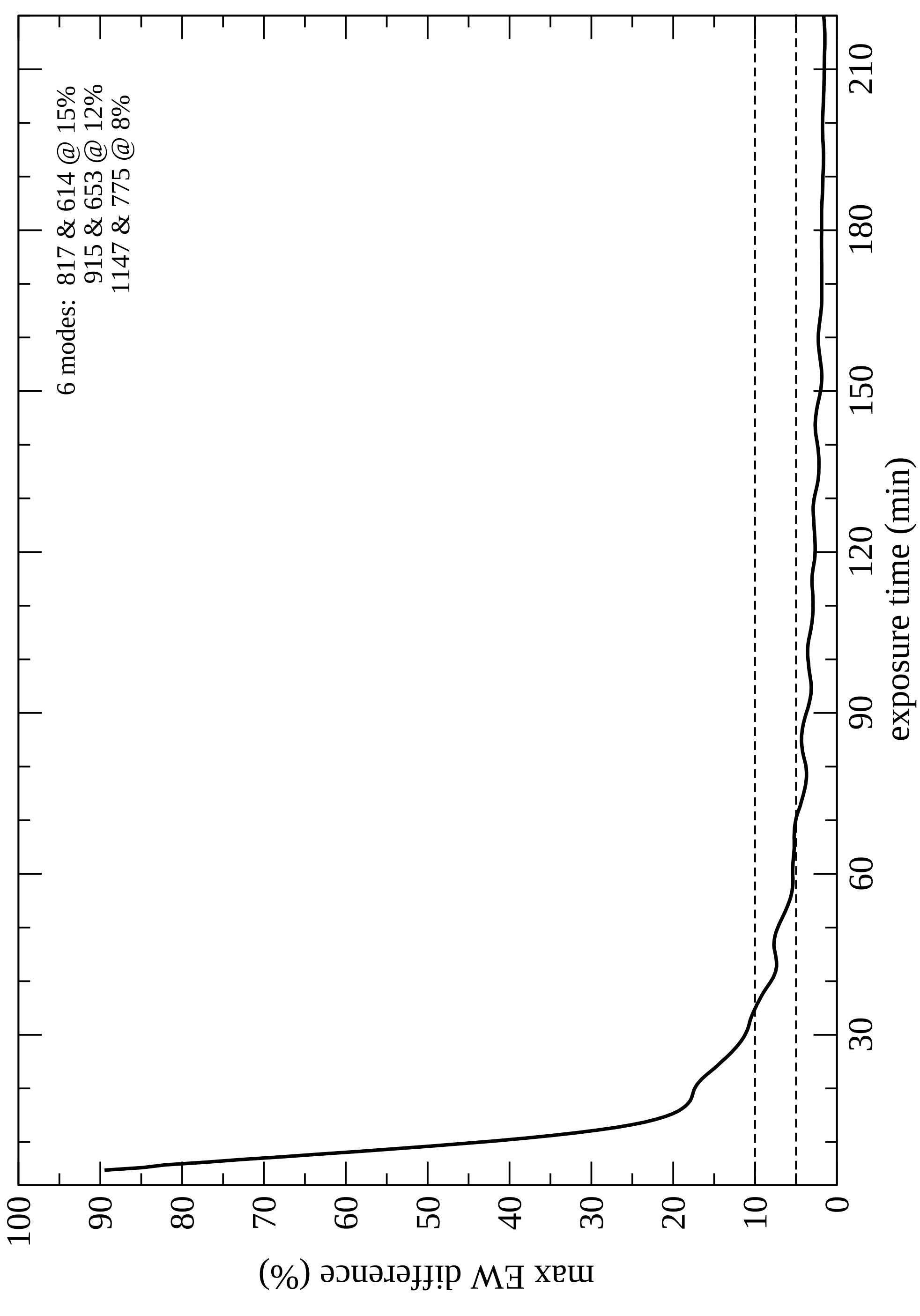

Fig. 3.— The maximum expected contribution of pulsations to EW variations for G29-38 as a function of the cumulative exposure time.

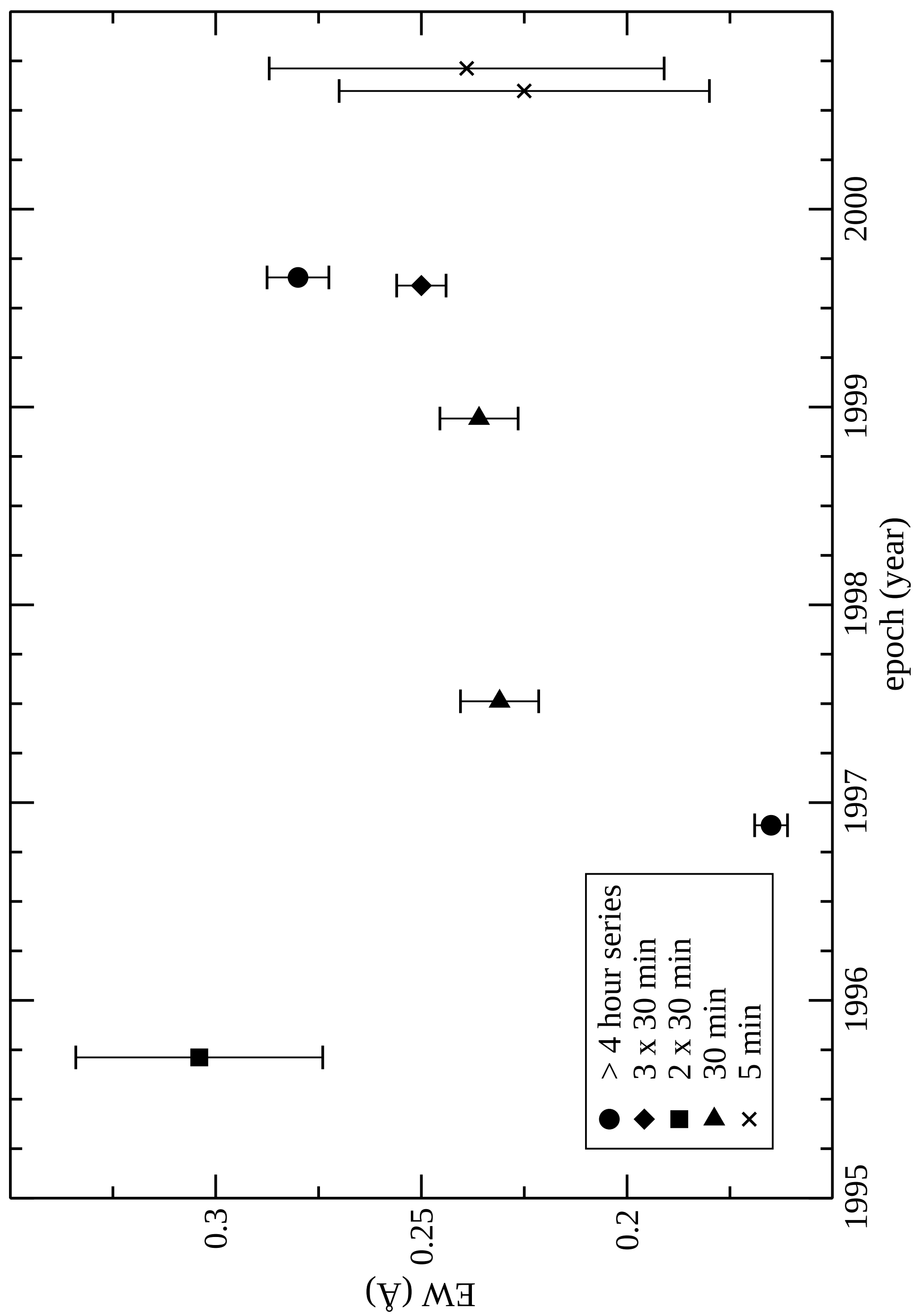

Fig. 4.— Calcium EW measurements for G29-38 at eight epochs over a five year period from three telescopes. The error bars are a quadrature addition of the uncertainty in the EW measurement and the expected variation due to sampling effects. Both error contributions decrease with longer exposures.